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A Critical Review of Fast Transient Breakdown in Solid Insulators

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Abstract

This report critically reviews currently available information on the subject of fast transient breakdown in solid dielectric insulators. Information is readily available on breakdown in solids under DC or low frequency conditions, as research into these areas has been driven by the power generating industries over many years. However, pulsed systems are generally constructed using safety factors or DC breakdown values for incorporated insulators. More recently fast transient (sub-nanosecond) breakdown in gases has been researched due to the use of gases in spark gaps.

The mechanisms involved in breakdown in solids under DC and low frequency AC conditions have been discussed and the relevance of these to breakdown under fast transient conditions has been explored. Also, theories that are pertinent to breakdown in solids under fast transient conditions have been reviewed. Measurement techniques for the collection of breakdown data have been examined and a test cell for the investigation of breakdown under fast transient conditions has been proposed. Statistical models that are used to describe breakdown in solids have also been discussed.

Executive summary

A critical review of currently available literature on the subject of sub-nanosecond breakdown in solid insulators has been undertaken. This review has sourced numerous papers, texts and reports from many of the key stakeholders active in this field. In particular, mechanisms and theories that are pertinent to the breakdown of solids under DC or low frequency AC conditions have been discussed. Zener theory, charge carriers, electron relaxation and field distortion have all been reviewed to identify their suitability in evaluating breakdown in solid insulators under transient conditions.

Standards currently used to measure the breakdown of solids under DC or AC conditions are also reviewed along with techniques used in the past to evaluate a materials electric strength. As a result of this, a test cell is proposed that would be capable of collecting reproducible electric strength data.

Statistical models have been investigated with particular attention being paid to the use of Weibull statistics in this field.

Recommendations for the continuation of this work are also included.

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1 Introduction

Insulator technology has evolved at a steady pace but has failed to keep up with the rapid advances in requirements. Improvements have come from using better fabricating materials and removing manufacturing flaws. Most, if not all of the research in this area, is being led by the power generation and distribution sectors whose requirements are at DC (Direct Current) and CW (Continuous Wave) at low frequencies. For such applications, design rules are available which allow the insulation elements of systems to be optimally sized and made reliable.

For repetitively pulsed systems the demands on insulator materials are very different. These tend to produce non-continuous waveforms, generally, a high voltage pulse (up to 1MV) with pulse lengths down to around 100 picoseconds, switched at some pulse repetition frequency, (e.g. kHz). The design rules for DC and low frequency applications do not apply; it is widely acknowledged that insulator materials are poorly characterised for such applications. Generally, breakdown fields are calculated on the basis of DC or low frequency data for the insulator resulting in larger systems than necessary.

The common requirement is to enable the design of high voltage, high prf (pulse repetition frequency) pulsed power systems of minimum volume, to withstand real-world (including military) environments and be amenable to low cost, serial manufacture. To meet this we need far better "design rules" for insulation elements and design techniques for systems than we have presently. The use of large "safety factors", now common, is not an option in the more demanding applications.

The subject of this report concentrates on the problem of non-ionising radiation (in the form of pulsed Radio Frequency (RF) energy) incident on solid insulators. The following are laid out as the aims for this project:

- Conduct a historical review of papers containing information pertaining to CW and pulsed waveforms through solids, liquids and gases. As part of this aim, the breakdown mechanisms will be discussed focussing primarily on issues pertinent to solid insulator breakdown.
- Investigate the time spectral evolution of some typical Ultra Wide Band (UWB) waveforms that are used in pulsed systems. This will include examination of the frequency content of the waveform incident on the insulating material.
- Identify parameters that are required to understand the breakdown of solid insulators under transient conditions.
- Discuss the impact of this study's findings on material selection.

The above aims will be covered in various sections throughout this report with a final section containing general conclusions and recommendations.

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2 Literature Review

Historically, research in this area has concentrated on breakdown in solid, liquid and gas insulators under CW conditions. The breakdown processes are well defined in this case and there are numerous equations from which an optimum lifetime for a given operating voltage can be obtained. For transient conditions, research over recent years has concentrated on breakdown predominantly in gas. It is felt that the task to completely investigate solid breakdown is too large and up until now little research has been completed in this area.

This section reviews papers and texts containing information relating to breakdown in solid, liquid and gas insulating materials under DC, low frequency AC and transient conditions. Bulk properties of solids will be investigated although specific mechanisms associated with breakdown in thin films are not discussed here.

It is important to have an understanding of how electric stress is defined. A popular text [1] on the topic of High Voltage (HV) breakdown gives the following definition:

"The electric stress to which an insulant is subjected is defined as the force, E on a unit charge placed in the insulant."

This definition means that the particles under the influence of the force E acquire kinetic energy. When this kinetic energy reaches a certain level, disruption of the insulant can occur by bombardment, rendering the insulant conducting. The voltage between two points (x_1 and x_2) equals the work done in moving the charge between them:

$$V_{21} = -\int_{x_2}^{x_1} E\,dx$$

Equation 2-1

Thus,

$$E = -\frac{dV_{21}}{dx}$$

Equation 2-2

Where V_{21} = Voltage between points 2 and 1 (V)

E = Electric field between x_1 and x_2 (V/m)

This result shows that the electric stress is numerically equal to the voltage gradient. The negative sign indicates that the motion from x_2 to x_1 is opposite to the direction of the field.

Further to the above definition, electric strength is used to define the maximum electric stress that a material can withstand. The definition of electric strength is complicated because of the various factors that control it. Pressure, temperature, waveform and impurities all influence the electric strength of a material. Some of these parameters are fairly simple to measure quantitatively, others are not so. It is the properties that control the electric strength of the material that are under investigation as part of this study and are discussed under the relevant sections below.

2.1 DC Breakdown

There is a wealth of information available concerning the breakdown mechanisms in solids, liquids and gases under Continuous Wave, CW or Direct Current, DC conditions. The majority of this information is contained in textbooks, for example [1], on the subject of High Voltage (HV) systems and has been summarised in this section.

2.1.1 Solids

Breakdown in solids as a result of a CW signal (e.g. DC) is well defined [1]. Electron avalanches and breakdown occur at stresses of approximately 10MV/cm if the material is highly purified and free of imperfections. The highest achievable breakdown stress achieved is known as the intrinsic electric strength of the dielectric. It is usual for dielectrics to breakdown before the intrinsic electric stress level is reached as a result of one of the following mechanisms:

2.1.1.1 Electromechanical Breakdown

When a voltage is applied to a dielectric an electrostatic force is incident upon it (as explained in the introduction to this section). This force results in compression of the dielectric and has the effect of increasing the effective electrical stress as the dielectric thickness decreases. Electrical failure results due to mechanical collapse.

This mechanism occurs at stress levels comparable to that of the dielectrics intrinsic electric strength.

2.1.1.2 Breakdown Due to Discharges

Breakdown may result from discharges occurring in voids or at surfaces. Figure 2-1 shows an example of a dielectric material with a void and the associated circuit diagram.

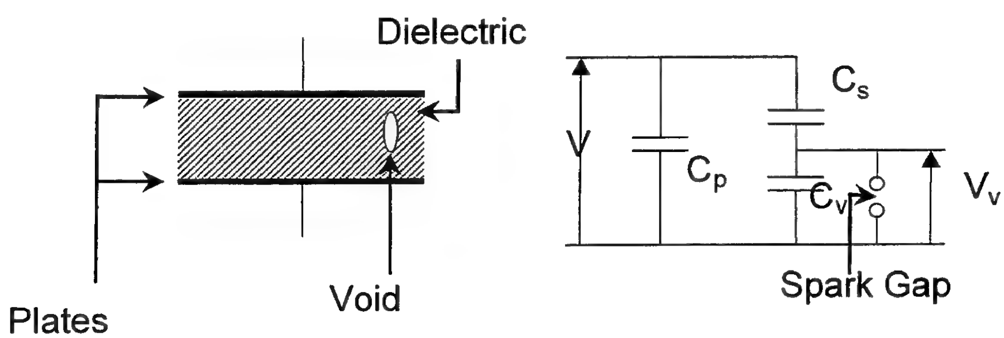

Figure 2-1: Dielectric material containing a void and the associated circuit diagram

The notation in Figure 2-1 is explained below:

C_p = Capacitance of the bulk of the dielectric

C_s = Capacitance of the solid dielectric in series with the void

C_v = Capacitance of the void

V = Voltage applied to the dielectric

V_v = Voltage across the void

The voltage across the void is given by:

$$V_V = \frac{VC_S}{(C_V + C_S)}$$

Equation 2-3

The spark gap in Figure 2-1 indicates that discharge can occur if V_v is sufficient. When sufficient voltage is reached discharge occurs collapsing the voltage. The voltage then rises again and the process is repeated. The walls of the void are eroded by charged particle bombardment so that the void lengthens causing field intensification and, ultimately, breakdown.

2.1.1.3 Thermal and Chemical Failure

Heat is generated as a result of dielectric losses. If this heat is not removed by a cooling process then the dielectric can burn out. As a result of thermal activity chemical reactions may take place between adjacent materials however, this is specific to the types and combinations of dielectrics in use and therefore the general rules do not apply.

2.1.1.4 Surface Breakdown

This can take the form of one of two mechanisms:

- Tracking – the formation of a conducting path on the surface of the material (degradation of the material)
- Surface flashover – breakdown of the medium in which the solid is immersed (e.g. gas) leading to breakdown of the solid. This form of breakdown is specific to the types of insulator in use and its geometry

2.1.2 Liquids

For highly purified liquids the breakdown mechanism is similar to that of gases (to be explained in section 2.1.3) and the associated intrinsic electric strength can be of the order of 1MV/cm. However, the nature of liquids is such that they are easily contaminated leading to the suspension of solids and dissolved gases. For a continually applied voltage (CW), field distortion occurs resulting in breakdown at a relatively low voltage. Under an electric field, dissolved gases may be released from the liquid in the form of bubbles, this is known as cavitation. As the gas in the bubble has a lower electric strength than that of the liquid, ionisation can occur. The discharges that occur in the bubble results in more gas being produced, leading to more bubbles and eventually breakdown of the liquid [1].

Due to contamination, liquids are used for applications where the CW voltage is incident at electric stresses less than 100kV/cm. It is possible to use solids in conjunction with liquids to allow operation at electric stress levels of approximately 1MV/cm. The solids act as barriers to the impurities and localises any bubbles that may form. The main function of the liquid in this case is to fill any voids in the solid, the effect of which has been discussed in section 2.1.1.

2.1.3 Gases

Electrons can be emitted from a cathode if the electric stress is high enough (of the order of 100kV/cm). This is known as field emission [1]. These free electrons are accelerated to the anode by the electric stress incident on them. They acquire kinetic energy during the acceleration and also lose energy as a result of collisions with other molecules. If the free electrons gain enough energy they can become ionising, knocking electrons out from other molecules resulting in positive ions. The consequence of this is an electron avalanche known as a Townsend Avalanche [2]. Increasing the voltage leads to secondary ionisation as the positive ions interact with the cathode. Ionisation increases with voltage until breakdown occurs.

An extension of the Townsend theory leads to Paschen's Law:

$$V_b = f(Pd) \qquad \text{Equation 2-4}$$

Where V_b = Breakdown voltage (V)

P = Pressure (mmHg)

d = Electrode separation (cm)

{f indicates a function}

The Paschen curve is regularly used to describe the variation of *f(Pd)* with breakdown voltage.

Finally, it is possible that free electrons may attach to molecules resulting in an electronegative gas. This process results in a high electric stress as the electronegative molecules are lost to the avalanche.

2.2 Low Frequency AC Breakdown

Research conducted under this topic focuses on the development of insulation systems used by the power generating and distribution industries. AC systems in this area (for example electricity substations) operate in the region of 50 – 100Hz for supply to homes via mains.

The breakdown mechanisms under low frequency AC conditions are covered under transient conditions discussed in section 2.3. Therefore, the application of insulators for use under low frequency AC conditions is discussed in this section.

2.2.1 Solids

The power generating industries are particularly interested in the electrical ageing of cables and other equipments that require the use of insulation. These industries are driven by costs and the ageing process can lead to breakdown resulting in the replacement of cables or components. In particular, there have been studies into the effects of ageing on polymers in cables and oil impregnated paper used in transformers [3]. The majority of these papers discuss electrical treeing leading to a discharge path for breakdown to occur.

Another area of interest is that of partial discharges which can be used to pre-empt breakdown in insulators. The power industries monitor systems (e.g. cables) for partial discharges so they know when equipment needs replacing. This monitoring can save money, as complete breakdown can be catastrophic leading to excessive repair bills.

2.2.2 Liquids

The primary liquid of interest to the power generating industries is transformer oil. This oil is often used as an insulator and/or a coolant in many transformer systems. Transformer oil, such as Shell Diala, is taken as having an electric strength of approximately 150 kV/cm when used in a gap of approximately 2.5 mm. However, when highly purified, an electric strength of approximately 1 MV/cm is achievable. Other oils [4] have been investigated as alternatives to the standard mineral oil including Coconut oil [5]. It is stated that the dielectric strength of Coconut oil exceeds that of standard transformer oil. In order to achieve this the authors purified the Coconut oil using a moisture reduction technique. However, they have not discussed the performance of purified Coconut oil with that of purified transformer oil, which has a much higher dielectric strength.

Other insulating liquids commonly in use are silicone (e.g. Dow Corning 200 or 561) or ester (Midel) based.

2.2.3 Gases

Sulphur Hexafloride (SF_6) and compressed air are two common gases used as insulation in capacitor systems. However, SF_6 is known to exhibit the greenhouse effect, have high sensitivity to conductor surface roughness and be costly in application [6]. Investigations into gas mixtures using SF_6 have yielded interesting results [6, 7, 8]. In particular it would seem that an 80% CO_2, 20% SF_6 mix has a higher dielectric strength than that of 100% SF_6 over a specific pressure range.

2.3 Transient Breakdown

With the exception of gas breakdown, the effects of transient waveforms through media have not been well studied. The large task that lies ahead of anyone investigating pulse breakdown in liquids or solids has been off-putting and as a result papers published concerning this topic are few and far between. Presently, design rules for the building of pulse power systems rely heavily on safety factors (see Section 1) for their construction. This results in a system that is more often than not larger than is required to operate at the field level for the given repetition rate.

It has been noted that pulsed breakdown voltages are typically 20% greater than those required for DC breakdown [2].

A major pioneer in pulsed power systems was J. C "Charlie" Martin. Martin worked at AWE during the 1960's and after many years of collecting data on breakdown he published several papers containing equations based on empirical observations. These equations are discussed in this section.

2.3.1 Solids

Martin stated that in the case of solids, breakdown originates in the volume of the material. Therefore, the effect depends on the volume and not the electrode area [9]. A caveat must be added to this statement. If the electrodes are greater than or approach the surface area of the insulator then field distortion or enhancement may occur leading to surface breakdown.

For a pulse duration in excess of a few nanoseconds the breakdown field is independent of the pulse duration and is given by:

$$E(vol)^{1/10} = k \qquad \textit{Equation 2-5}$$

Where E = Breakdown field (MV/cm)

k = constant dependent on material type

In addition to this, consideration has been given to the effect of repeating pulses resulting in the following expression:

$$N = \left[\frac{E_{BD}}{E_{op}}\right]^8 \qquad \textit{Equation 2-6}$$

Where N = Number of repetitions before breakdown

E_{BD} = Breakdown field

E_{op} = Operating field

Equations 2-5 and 2-6 are based on empirical data collected by pioneers in pulse power research in the 1960s and are still used to predict breakdown in solids today.

2.3.2 Liquids

The effect of impurities as discussed in section 2.1.2 is small for pulses of the order of 10μs [1]. Under CW conditions it is the lining up of the impurities that leads to field distortion, which in turn leads eventually to breakdown. However, the alignment process in most liquids is moderately slow and is unlikely to affect the electric strength on pulses lasting less than approximately 1ms.

Empirical observations have shown the following relationship for uniform fields:

$$Ft^{1/3}A^{1/10} = k \qquad \text{Equation 2-7}$$

Where F = Breakdown field (MV/cm)

t = Time (μs)

A = Electrode area (cm^2)

k = Constant dependent on liquid

A correction to Equation 2-7 is required where the field is not uniform i.e. a conductor can perturb the field distribution leading to an increased electric stress.

2.3.3 Gases

For gaps in air the following equation describes the breakdown field:

$$E = 24.6p + 6.7\frac{p^{1/2}}{d^{1/2}} \qquad \textit{Equation 2-8}$$

Where E = Breakdown field (kV/cm)

p = pressures (atmospheres)

d = gap distance (cm)

Using Equation 2-8 for a gap of 1cm with a pressure of 1 atmosphere yields approximately 30 kV/cm which is generally accepted as the intrinsic electric strength of air.

For divergent fields around points or edges the following relationship holds for gaps greater than 10cm:

$$F \pm (dt)^{1/6} = k \pm p'' \qquad \textit{Equation 2-9}$$

Where F = Mean breakdown field (kV/cm)

d = electrode spacing (cm)

t = time (μs)

p = pressure (atmospheres)

k and n vary depending on the gas between the electrodes.

2.4 Summary

This section has summarised the historical information pertaining to research conducted into the breakdown of solid, liquid and gas insulating materials. As initially stated there has been little research completed on the topic of breakdown in solids under pulsed transient conditions. Pulsed power systems rely heavily on solids in the form of supporting structures and enclosures as well as internal insulation.

Analysis of sub-nanosecond breakdown in solid insulators and an investigation of why intrinsic electric strength is not readily achieved is dealt with in the following section.

Further information about specific models and equations that may be used to describe breakdown in solid insulators can be found in Annex A.

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3 Breakdown in Solids under Transient Conditions

The mechanisms of breakdown in solid, liquid or gas insulating materials have been discussed in Section 2. It is now necessary to investigate the processes involved during breakdown in solids under transient conditions more thoroughly.

3.1 Investigation of Typical UWB Pulses

Pulses that are of interest to the topic of this report can be described as Ultra Wide Band (UWB) in nature, indicating a fractional equivalent bandwidth of >25% of the centre frequency. The usual frequencies seen in UWB pulses are in the range of 1MHz to > 10GHz. Two actual UWB pulses used in pulsed power systems are now discussed. These pulse types have been labelled Type 1 Transient and Type 2 Transient to avoid classification issues. Figure 3-1 shows a Type 1 Transient of the order of several nanoseconds in duration and is the output of a discharge across a spark gap. This data has been Fourier transformed so that the frequency content can be analysed, this FFT (Fast Fourier Transform) is shown in Figure 3-2.

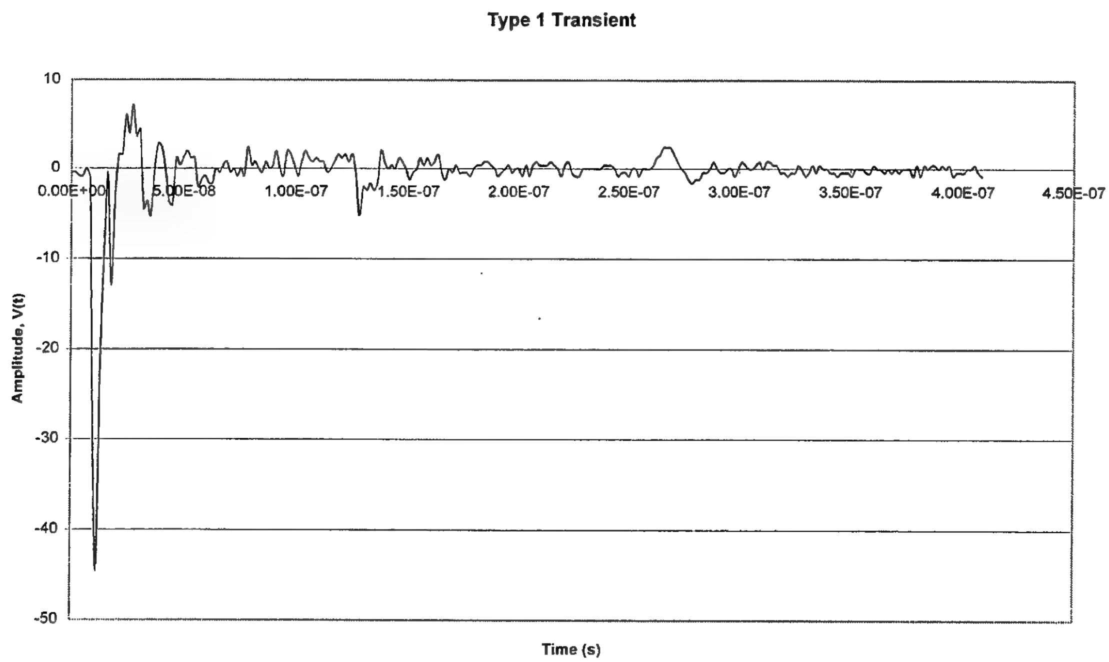

Figure 3-1: Type 1 Transient

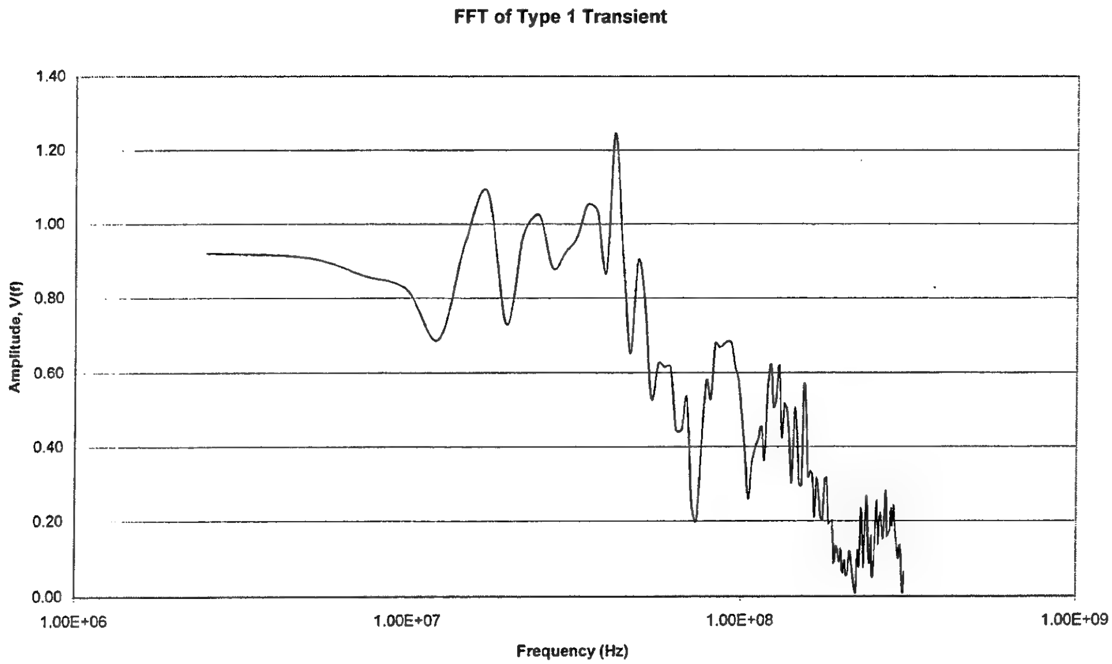

Figure 3-2: FFT of Type 1 Transient

It can be seen that the frequency content of this complex transient lies between 5MHz and 318MHz. The maximum frequency content of the pulse relates to the fastest time component in the pulse. This is obtained by using Equation 3-1.

$$T_{\max} = \frac{1}{f_{\max}}$$ *Equation 3-1*

Therefore, the fastest time component of the Type 1 Transient given in Figure 3-1 is $1/318*10^6$ = 3.14ns. This information is important from a breakdown perspective and will be further discussed later.

For comparison, analysis of a Type 2 Transient pulse has been completed. It should be noted that the Type 2 Transient represents the faster end of the sub nanosecond regime and is typical of the output of a ferrite sharpening line. Figure 3-3 shows the Type 2 Transient in the time domain and Figure 3-4 shows the frequency domain content after a FFT has been performed.

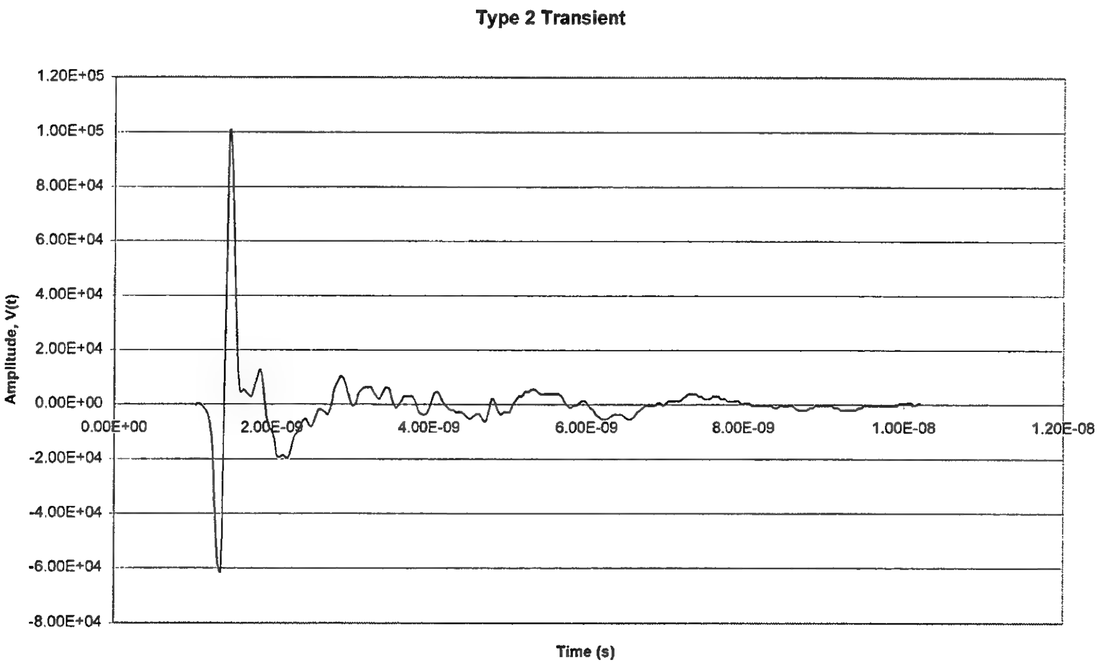

Figure 3-3: Type 2 Transient

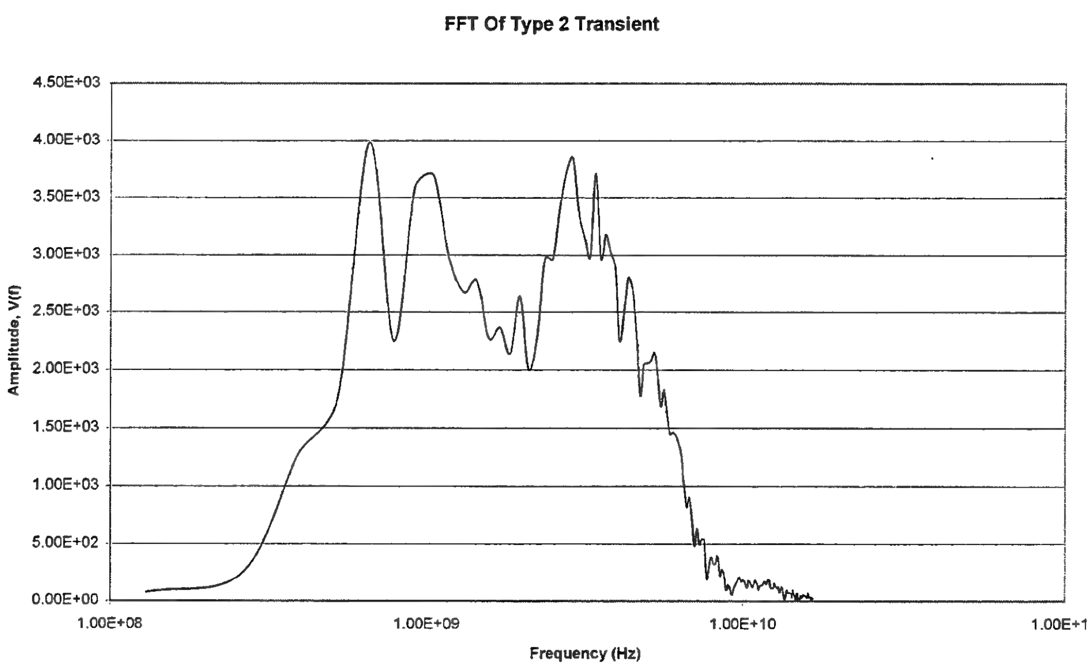

Figure 3-4: FFT of Type 2 Transient

The frequency content of the Type 2 Transient lies between 130 MHz and 17 GHz; however, there is no significant contribution to the transient above approximately 9 GHz. Using Equation 3-1 it is

possible to work out the fastest component of the Type 2 Transient pulse. The maximum significant frequency content is 9 GHz therefore, $1/9*10^9$ = 111ps.

In order to assess the impact of these two transients it is necessary to investigate where the energy lies within certain frequency bands. It can be seen from Figures 3-2 and 3-4 that there is no frequency content in either the DC or low frequency AC regime. Table 3-1 shows the percentage contribution to the overall energy for the frequency ranges specified.

Frequency range	% Energy content	
	Type 1 Transient	Type 2 Transient
<10MHz	7.9	0
10MHz – 50MHz	29.3	0
50MHz – 100MHz	22.8	0
100MHz – 200MHz	27.8	0.1
200MHz – 300MHz	11.4	0.2
300MHz – 400MHz	0.8	1.0
400MHz – 500MHz	0	0
500MHz – 600MHz	0	1.3
600MHz – 700MHz	0	3.0
700MHz – 800MHz	0	1.7
800MHz – 900MHz	0	0
900MHz – 1GHz	0	2.7
1GHz – 2GHz	0	16.2
2GHz – 3GHz	0	18.3
3GHz – 4GHz	0	16.5
4GHz – 5GHz	0	13.8
5GHz – 6GHz	0	10.8
6GHz – 7GHz	0	5.3
7GHz – 8GHz	0	3.0
8GHz – 9GHz	0	1.5
9GHz – 10GHz	0	0.8
>10GHz	0	3.8

Table 3-1: Energy contribution for specified frequency bins

The data given in Table 3-1 can also be seen in Figure 3-5.

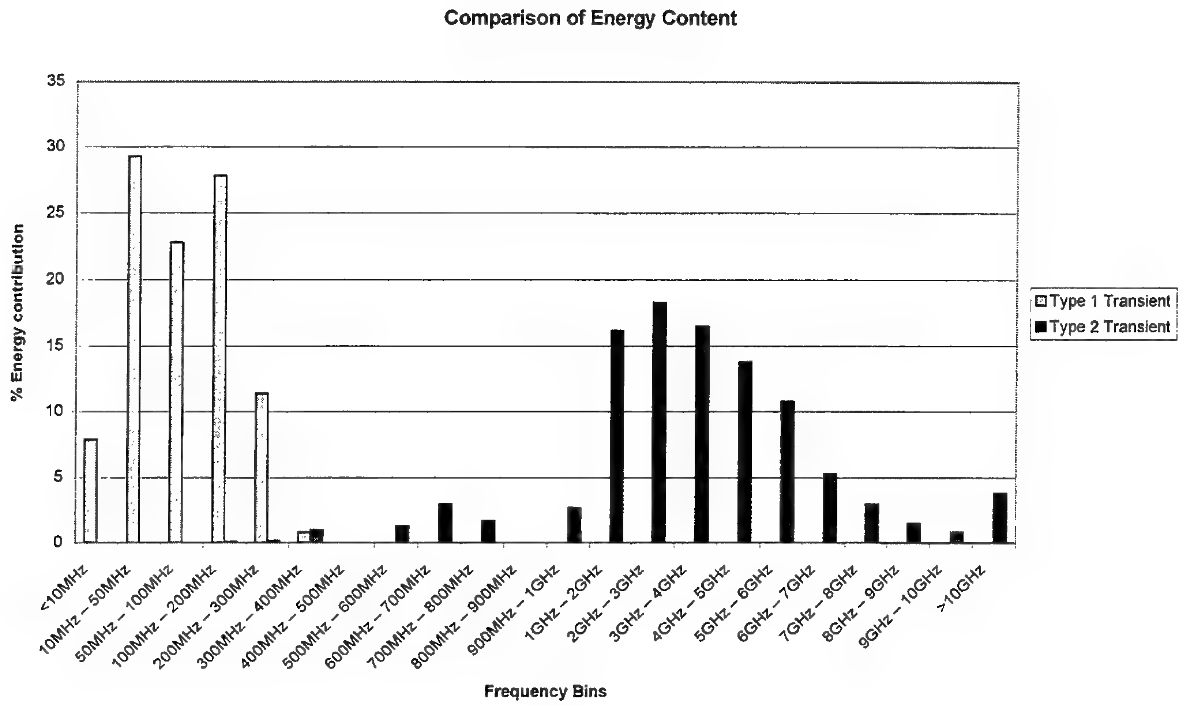

Figure 3-5: Comparison of the Energy Content of Type 1 and 2 Transients

Figure 3-5 shows that the frequency content of the Type 1 Transient does not exceed 400MHz. The conclusion from this information is that there are no sub-nanosecond components in the Type 1 Transient. However, for the Type 2 Transient there exists frequency content in excess of 10GHz which relates to picoseconds in the time domain. This highlights the importance of analysing the waveforms that any insulator will be subjected to. For these two transients there is no contribution to the energy by either DC or low frequency AC.

In Section 2 one of the principal breakdown mechanisms identified was that of thermal breakdown. For single pulsed systems thermal breakdown is unlikely to occur as there will not be enough time for the heat to build up i.e. the thermal conductivity from the insulator to the surrounding material is sufficient enough to remove the heat energy before any thermal damage can occur. The maximum energy at which thermal breakdown occurs in a typical polymer is between 60kJ and 100kJ [10]. Therefore, the energy content of any incident pulse would need to exceed these levels for thermal breakdown to occur. The exception to this is in the case of systems that employ high pulse repetition frequencies (prf). If the prf is sufficient enough to overcome the effect of thermal conductivity then thermal breakdown may occur. For example, the Type 1 Transient analysed in section 3.1 has an energy content of approximately 4J which, in the case of a single pulse, would be insufficient to cause thermal breakdown. In the case of repetitive pulses the prf would have to be limited to between 15kHz to 25kHz to ensure that thermal breakdown could not result. The duty cycle of the pulse would also need to be considered, as when the energy is not present thermal conduction will be occurring.

It is now necessary to see how the fast transients and the information that can be obtained from them apply to breakdown in solids. The literature review completed as part of Section 2 has highlighted three theories of particular interest that concern breakdown in solids.

3.2 Zener Theory

When solid insulators are considered in terms of their band structure there exists a valance band full of electrons and a conduction band that is void of electrons. Between the two bands is a band gap known as the forbidden region (where electrons are not allowed). This model holds for materials at absolute zero but for temperatures above this (and due to manufacturing defects) there will be some electrons in the conduction band. Under the influence of a critical electric field strength, dielectric breakdown occurs leading to an increase in the number of electrons in the conduction band.

Zener [11] proposes that a 'tilted' band structure as seen in Figure 3-6 be considered in the presence of an electric field.

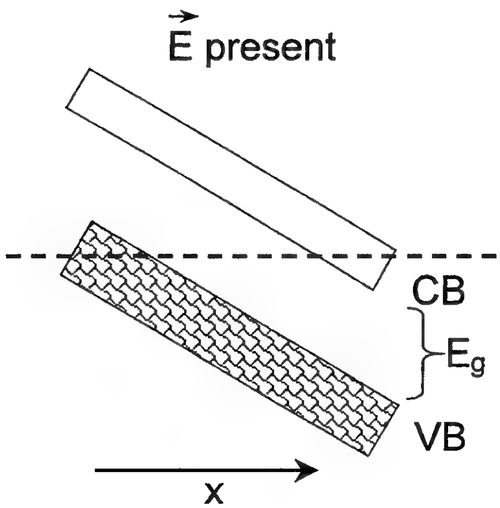

Figure 3-6: Tilted band structure as discussed by Zener Theory

The notation used in Figure 3-6 is as follows:

E = Electric Field

x = direction of Electric Field

CB = Conduction band

VB = Valence band

E_g = Band gap (forbidden region)

With the presence of the Electric Field (E) the dotted line shows the path that electrons can take from the valence band to the conduction band without the extra energy required to cross the forbidden region when no field is present. The magnitude of the electric field determines the rate of transfer of the electrons from the valence band to the conduction band. Zener Theory states that the band gap can be considered as a barrier and the problem then becomes one of quantum mechanics (tunnelling).

The tunnelling rate (γ) obtained by Zener is given in Equation 3-2:

$$\gamma \cong \frac{eFa}{h}\exp\left\{-\frac{\pi^2 ma\varepsilon^2}{h^2|eF|}\right\}$$

Equation 3-2

Where e = electron charge (esu)

F = Electric Field (esu/cm)

a = lattice constant (cm)

h = Planck's constant (erg s)

m = mass (g)

ε = energy gap between CB and VB (erg)

Assuming reasonable values of ε = 2eV (using 1eV = 1.602e^{-12} erg) and a = 3*10^{-8} cm, Equation 3-2 is simplified to Equation 3-3:

$$\gamma = 7.2*10^6.F.10^{-\frac{0.4*10^7\varepsilon^2}{F^*}}$$

Equation 3-3

In Equation 3-3, F^* is expressed in V/cm using the relationship 1 esu = 300 V.

Plotting the tunnelling rate against typical values of electric field yields Figure 3-7.

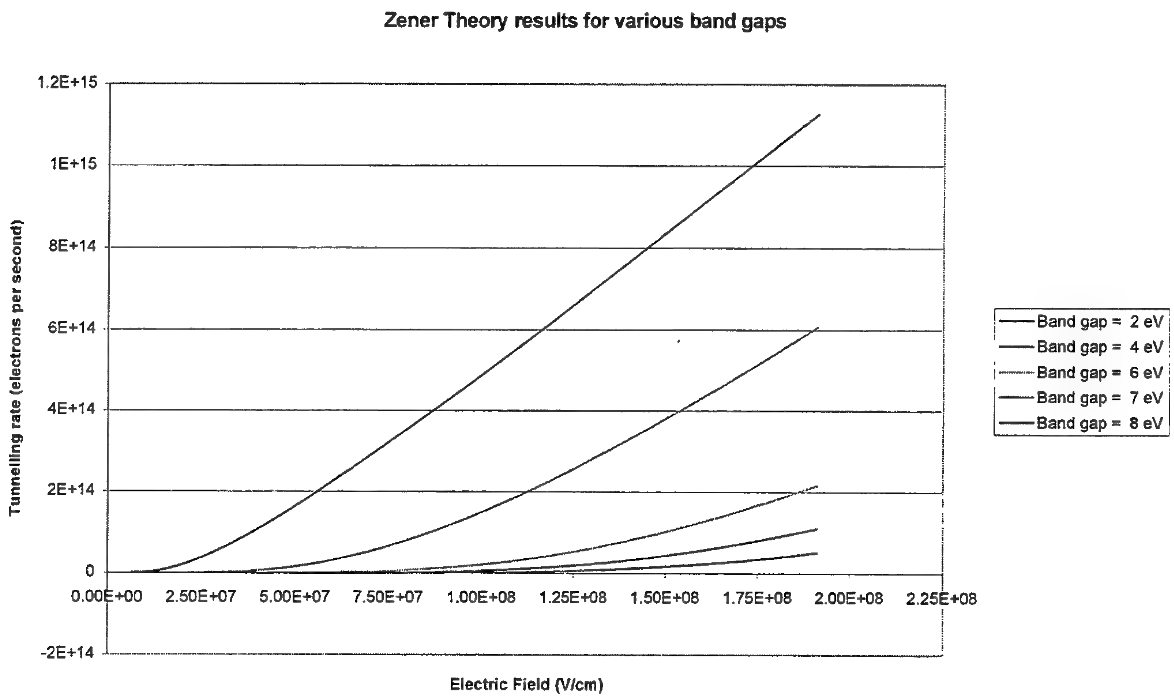

Figure 3-7: Tunnelling Rates as predicted by Zener Theory

Zener Theory predicts that significant electron tunnelling from the valence band to the conduction band occurs at approximately 25MV/cm for a solid with a band gap of 2eV. Polymers typically have band gaps of the order of 7eV. It can be seen in Figure 3-7 that tunnelling does not have any significant effect until a field strength of approximately 125MV/cm is applied. Empirical observations show that breakdown occurs in polymers at field levels much lower than 125MV/cm at approximately 2.5MV/cm [12]. It has been suggested that Zener theory is only applicable to

semiconductors where the junction is sufficiently narrow to allow tunnelling to occur [13]. However, it is possible that Zener theory describes the intrinsic electric strength of solids and therefore indicates the maximum field strength that can be expected before breakdown occurs.

3.3 Charge Carriers

The movement of charges inside solids have been discussed as possible causes of breakdown in solids due to an applied electric stress [14]. In particular the movement of individual charges (either free electrons or holes) moving along a lattice as a result of the applied electric field is of interest to the topic covered by this report. By considering the movement of a charge *q* with a velocity *v* moving along the z-plane as shown in Figure 3-8, it is possible to calculate the parallel and normal components of the induction at a distance *a* from the trajectory of the particle.

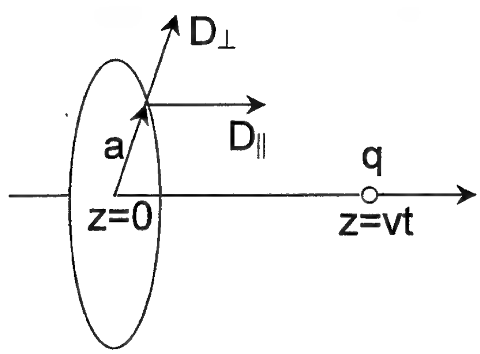

Figure 3-8: Parallel and normal components of dielectric induction at a distance a from the trajectory of the charge

At a time *t* the charge has moved *z=vt* along the z-axis. The movement of the charge along this axis results in dielectric induction at points away from the z-axis. The strength of this induction is made up of both normal and parallel components dependant on the distance from the trajectory of the charge and is defined by Equations 3-4 and 3-5.

$$D_{\parallel} = \frac{q}{4\pi} \frac{vt}{\left(a^2 + v^2 t^2\right)^{3/2}}$$ *Equation 3-4*

$$D_{\perp} = \frac{q}{4\pi} \frac{a}{\left(a^2 + v^2 t^2\right)^{3/2}}$$ *Equation 3-5*

Where $D_{\parallel}$ = Parallel component of the dielectric induction (H)

$D_{\perp}$ = Normal component of the dielectric induction (H)

q = charge (C)

v = velocity of charge (ms^{-1})

a = distance from charge path (m)

t = time (s)

It is important to consider the time dependence of these components. The parallel component changes sign as the particle passes through the reference plane (t=0) whereas the normal component rises and falls gradually without changing sign. The rapid reversal of the parallel component leads to the generation of a high electric field (due to the slowness of the medium

response) which drives the polarisation[1] at the high rate required. This rapid reversal has been demonstrated to have high energy dissipation associated with it [16] leading to problems arising from the lack of thermal conduction (i.e. energy in the form of heat is not being led away from the medium). The energy dissipation is increased as v increases and as a decreases. It is also stated [14] that the reversal of the polarisation results in a smaller residual longitudinal polarisation. This in turn leads to a 'tunnel' of residual polarisation decaying with time as the charge moves along the z-plane. An interesting point here is that the residual charge represents a lowering in the potential for any following charge resulting in a preferential path for any other charges following q. Once the field reaches a certain level, positive feedback occurs resulting in an increasing 'tunnel'. The energy dissipation from the dielectric caused by the particles (and their associated charge) leads rapidly to thermal destruction in the form of catastrophic breakdown. Again, it is felt that this mechanism is only valid for systems employing high prf.

The most effective particles from a breakdown viewpoint are those that have significant dielectric loss [14]. These are generally particles whose velocity is in the direction of the prevailing electric field resulting in a critical frequency. This critical frequency (ξ) is defined as the frequency at which the energy in one half-cycle of a harmonic oscillation occurs at and is given in Equation 3-6.

$$\xi = \frac{v}{40\pi\, r_0}$$

Equation 3-6

Where v = charge velocity (ms^{-1})

r_0 = radius at which dielectric induction vanishes (m)

Materials that are least likely to suffer breakdown are those with low dielectric loss in frequencies at or close to the critical frequency as defined by Equation 3-6. For a free electron in a solid the critical frequency is of the order of 10^{14} Hz (100 THz). This information could be used in conjunction with dielectric loss (also known as loss tangent) measurements to identify materials that are more likely to suffer breakdown. For example, measurements of dielectric loss were made on Perspex and polyethylene [17]. For Perspex the dielectric loss was greatest at 100 kHz (0.0283 radians) whereas for polyethylene the dielectric loss was greatest at 11 GHz (0.0002 radians). This implies that the electric strength of polyethylene should be greater than that of Perspex as the loss tangent for Perspex is greater. This agrees with empirical observations for the electric strength of polyethylene (370 kV/cm) and Perspex (140 kV/cm) [18]. This is an important result as it implies that the loss tangent could give an indication of the electric strength of a material.

3.4 Impulse Breakdown

The IEEE specify a withstand impulse for the testing of certain HV systems. This impulse has a rise time (time to peak amplitude) of 1.2μs and a FWHM of 50μs. The peak amplitude is of the order of 1.2MV and the pulse is generally used as a lightning test. Comparison of a 1/5 impulse with a DC test was made which indicated that there was no significant difference in the electric strength [19]. A decrease in the electric strength of a material when the pulse duration increases has been noted [19]. This is as expected as the energy content of the pulse will increase as the pulse duration increases. The influence of pulse duration increased as the thickness of the sample decreased. Again, this is as expected as the energy content of the pulse will become dominant over smaller thickness' of insulator (i.e. less of a barrier for breakdown to occur across). An interesting observation was made during this work, that is that neither silica nor polystyrene showed any significant thickness effect with respect to pulse duration.

[1] Partial separation of electric charges in an insulator under the influence of an electric field [15]

Another interesting observation is that of the effect of the 'steepness' of the rising edge of the pulse [20]. It is stated that the electric strength of the solid increases as the 'steepness' of the rising edge of the pulse increases if the time of this stress is less than approximately 10^{-7}s (100ns). Also, the electric strength of the solid decreases for breakdown occurring at the tail of the pulse as the 'steepness' of the rising edge increases. 'Steepness' can be considered to be $\frac{dV}{dt}$ i.e. a measure of the 'stress' of the pulse. This implies that if the pulse is highly stressing i.e $\frac{dV}{dt}$ is large (as with typical UWB pulses such as those analysed in section 3.1), then the solid becomes more susceptible to the remainder of the pulse. It is worth noting that these points are observations, no qualitative data is available that suggests the actual mechanisms involved.

3.5 Electron Relaxation

The relaxation time of a free electron lies between 10^{-13} to 10^{-15} seconds [21]. To directly excite a free electron it would be necessary to irradiate the insulator with RF energy of the order of 10 THz ($1/10^{-13}$) to 1 PHz ($1/10^{-15}$). These frequencies are not of concern to the pulsed power system designer at the time of the preparation of this report as the maximum rise times (or maximum change in Voltage amplitude) are of the order of 10^{-12}s (ps).

3.6 Field Distortion

At the high frequencies associated with sub-nanosecond breakdown the geometry of the conductors at the boundary with the insulator becomes significant. Sharp edges on conductors can lead to field enhancement as a result of field distortion provoking breakdown and especially surface discharge. However, field enhancement is very specific to the geometry of the system and is therefore very difficult to describe in the general case.

3.7 Summary

Theories that are applicable to breakdown under transient conditions have been discussed in this section. Time spectral analysis has been performed on two typical pulses used in pulsed power applications. This analysis has highlighted that typical transients cannot be considered in terms of their DC or low frequency AC components as these do not exist.

Zener Theory could be useful for ascertaining the intrinsic electric strength of a material. Although, it is worth noting that the actual electric strength will be dependant on manufactures defects, the existence of any voids, the geometry of the material, the volume etc and some statistical element. This will be discussed in a later section.

It may be possible to use Zener theory as an indicator of a materials intrinsic electric strength as suggested in Equation 3-7:

$$E_{bd} = k\varepsilon \qquad \textit{Equation 3-7}$$

Where E_{bd} = Breakdown field strength (V/cm)

k = constant of proportionality

ε = band gap of material (eV)

By investigating materials with known electric strengths and known band structure a constant of proportionality could be found and this, in turn, could be used to predict the electric strength of materials with known band structure but in cases where the electric strength is not known.

An insulator may be more vulnerable to breakdown at specific frequencies due to the material becoming dielectrically more lossy. It becomes necessary to either limit that frequency component

or select a more suitable material for a given application. An understanding of the dielectric loss tangent of a material will be useful for identifying materials that are more likely to suffer breakdown at lower electric strengths. This will impact on material selection.

A measure of the thermal conductivity of the solid is also useful for determining the maximum limit of stress before the onset of thermal breakdown.

It is necessary to investigate measurement techniques that are used to monitor breakdown in solids. This will be discussed in the following section.

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4 Measuring the Electric Strength

Previous sections have concentrated on defining important issues and theories supporting the subject of this report. In this section, measurement techniques that are used to assess the electric strength of materials are discussed.

The techniques that are discussed have been used to investigate the electric strength of solids for many years. It is expected that these techniques will be suitable for the assessment of solids to fast transients and this is also discussed.

4.1 Standards

Several standards exist for evaluating the electric strength of materials. In particular IEC 60243 describes test methods for direct voltage [22], power frequencies [23] (48Hz – 62Hz) and lightning impulses [24]. None of these standards cover methodologies for the assessment of breakdown under fast transient conditions (i.e. sub-nanosecond breakdown). All of these methodologies are covered by a single IEEE standard [25]. A typical set-up for the assessment of electric strength as given by IEC 60243 is shown in Figure 4-1.

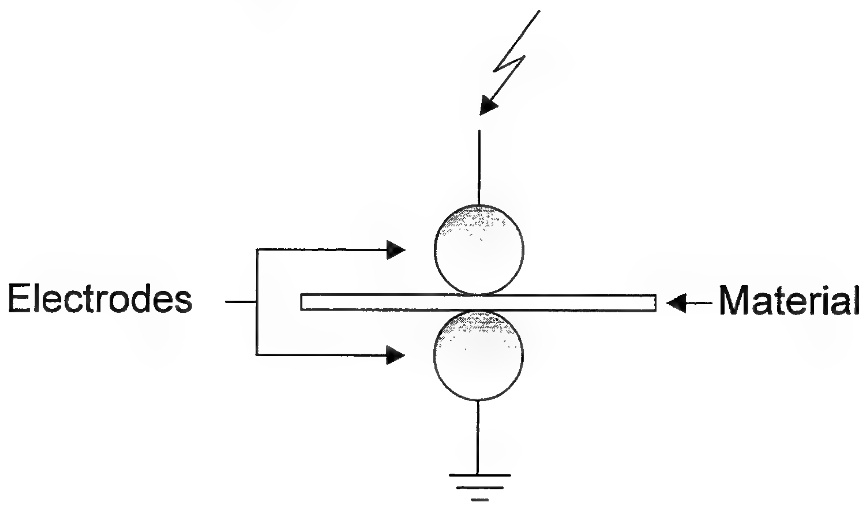

Figure 4-1: Test set-up for the assessment of a materials electric strength

The electrodes used must be of a specific diameter and there exists a standard thickness for the material under test so that results from different materials can be compared. In the case of direct voltage, the voltage is increased at a rate at which the majority of failures occur between 10 and 20 seconds. For impulses, sets of three pulses of equal peaks are applied. The first set of pulses takes place at 70% of the peak voltage expected to cause breakdown. The following sets have their peak increased by 5-10% until breakdown occurs. It is expected that the charging time of the generator used to apply the pulse will be greater than the time taken for the energy to be fully distributed throughout the material therefore successive pulsing is acceptable.

4.2 Manufacturers' Qualification Tests

Manufacturers often specify breakdown voltages as a result of a qualification test. This is generally a set of tests completed on a typical sample of the material being sold. The tests are not usually repeated unless part of the manufacturing process changes. These types of tests are typically used on insulated cables to understand their limits in the way of voltage rating. An example of a qualification test is the AEIC procedure [26] used for evaluating the breakdown voltage on power cables. This test includes both a high-voltage time test and an impulse breakdown test. The high voltage time test involves running the cable at a given voltage for a period of time (hours) before increasing the voltage. This steady voltage increase is repeated until breakdown occurs. The impulse test follows a similar method as for IEC 60243.

4.3 The 'Recessed Specimen' Method

A plane disc of the specimen to be investigated has a spherical depression either ground in or machined leaving approximately 30-100μm thickness at the thinnest point [27]. A thickness of this order allows breakdown to occur at reasonable voltages whereas a larger thickness would require higher voltage to initiate breakdown. A typical test set-up using the 'Recessed Specimen' method is shown in Figure 4-2.

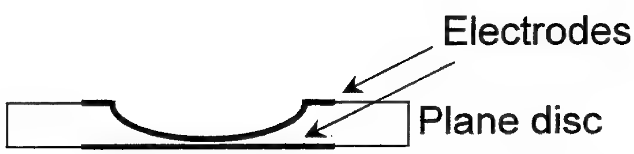

Figure 4-2: The 'Recessed Specimen' Method

The surfaces are made conducting with the use of an aluminium film which ensures good contact with the dielectric. The voltage to the electrodes is then increased systematically until breakdown occurs. Alternatively, under pulsed conditions the peak voltage of the pulse is increased until breakdown occurs.

The limitations to the recessed specimen method are that firstly, thermal conductivity away from the material is poor therefore thermal breakdown has a higher probability of occurring. Secondly, the thin nature of the area under test leaves it open to the effects of mechanical force (especially under compression of the electrodes) rendering the material buckled and damaged [27]. It may be possible to reduce this effect by way of supporting the test specimen, however, any support would have to be non-invasive to the test set-up and have no effect on the outcome of the test.

4.4 The McKeown Technique

The McKeown technique [27] uses two ball bearings as electrodes located within a cylindrical hole in a plastic disc. The lower ball is held in place with resin and the sample to be tested is placed on top of the lower ball. The top ball is placed on top of the sample and the set-up is cured until it is solid. The McKeown technique is shown in Figure 4-3.

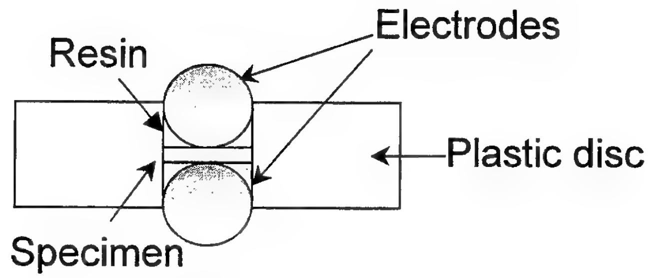

Figure 4-3: The McKeown Technique for assessing electric strength

It is essential that the surface of the sample under test adheres to the resin otherwise premature breakdown may occur due to discharges. It is stated that a 'McKeown' specimen of polythene withstood in excess of 15000 hours without incurring breakdown under an applied field strength of 1.7MV/cm [27].

4.5 Test Cell

In the standards described above the electrodes are incident on the material at specific points so that the breakdown path can only take one route. If the electrodes are not in direct contact with the material under investigation, breakdown of the air around the test arrangement could occur at levels considerably lower than that expected of material breakdown (air breakdown is quoted as being approximately 30kV/cm [9]). Any test set-up used for fast transient analysis should use a similar system to those used in the standards described in section 4-1 to ensure that the results are comparable.

It is anticipated that the 'Recessed Specimen' Method, the McKeown Technique or the techniques defined in the IEEE and IEC standards would be suitable for assessing the electric strength of solids under fast transient conditions. However, some modifications are required and these are mentioned later. All of these techniques use electrodes that are incident on the material under investigation. The simplest technique to employ would be as defined in the IEEE and IEC standards and shown in Figure 4-1. This technique requires little preparation of the material prior to test compared to the recessed specimen method and the McKeown technique. Some preparation may be required in the form of maintaining the thickness of different materials under test. This is important to allow direct comparison between results as the volume of the sample (and therefore thickness) will affect the electric strength [12].

In order to gain confidence in the breakdown voltage for a specific material it is necessary to test a number of samples. The larger the number the more statistically significant the results become. The breakdown voltage of the material should be given as the mean value of the voltage at which breakdown occurred for all samples tested.

It may be possible to estimate the occurrence of breakdown by monitoring specific material parameters. For example, the complex permittivity should change as breakdown nears. Partial discharges have already been discussed (see section 2.2.1) and these are used to pre-empt breakdown. Tests should be completed with a variety of materials at various thicknesses during which the complex permittivity could be monitored.

For fast transients the geometry and therefore the impedance of the test cell become important factors. It is also necessary to consider not only the cell and electrode geometries but also the source and cable interconnections. Cables play a critical role in ensuring that the generated pulse reaches the material without any changes in rise time, amplitude or frequency content. Any cables used must also be able to withstand the test pulse. Figure 4-4 gives an example of a test set-up for investigating breakdown under transient conditions.

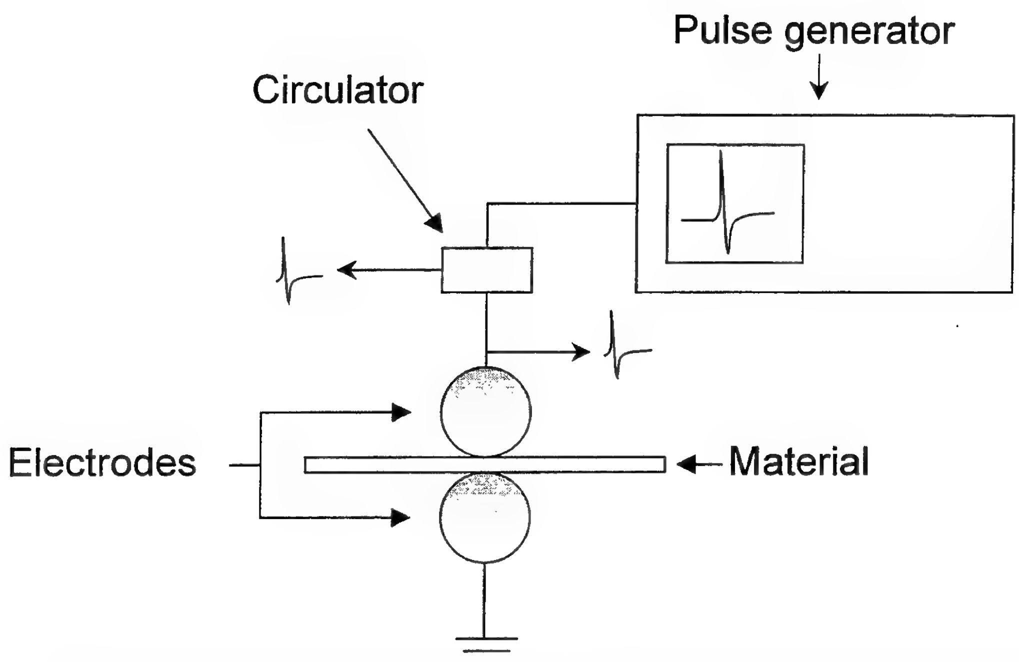

Figure 4-4: Test set-up for investigation of breakdown in solids under transient conditions

The set up shown in Figure 4-4 allows for the investigation of breakdown in solids under transient conditions. The pulse generator sends the pulse into a cable that is connected to a circulator with low group delay to ensure that there is no significant change in the rise time and peak amplitude of the pulse. The pulse continues on to the electrode where it interacts with the material under test. If the amplitude is insufficient to cause breakdown then the pulse will be reflected back up the cable into the circulator where a measurement can be made on any attached instrumentation. The reflected energy does not pass back into the pulse generator thereby ensuring that unnecessary damage does not occur. Conversely, if the pulse has sufficient amplitude to cause breakdown in the solid then the energy will continue through the insulator to the ground connection. Thus, there will be no reflected energy and no pulse will be measured at the circulator. This is a useful measurement point, as it may not be obvious that breakdown has occurred. The circulator, in this instance, will also protect the generator from driving into a short circuit.

To ensure that the generated pulse is indeed the pulse incident on the material under test an additional measurement point has been included after the transition through the circulator and before the pulse interacts with the insulator. It is likely that the circulator will have some intrinsic attenuation (of the order of 0.5dB) and this measurement point is necessary to reduce the uncertainty in any quoted results.

It is essential that the test cell components are electrically matched so that there are no areas where the pulse can be degraded. The cables, connectors, pulse generator outputs, circulator and electrodes all need to be matched so that pulse degradation is reduced. It is likely that the system will need to be impedance matched to 50Ω as this will probably be the output impedance of the pulse generator and the input impedance of any instrumentation used.

4.6 Summary

Several measurement techniques have been discussed that will allow evaluation of a materials' electric strength. Standardisation of the volume of the sample is an important factor in this process and the dependence of breakdown on this parameter has been discussed.

Consideration has been given to the optimum method of testing a solid for its electric strength. The need for multiple samples to be tested has also been mentioned due to the need of reducing statistical uncertainty in any results. The application of statistics in this subject will be discussed in the following section.

A possible configuration for a fast transient test cell has been proposed. This would allow the collection of breakdown data in solids under fast transient conditions.

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5 Statistical Models of Dielectric Breakdown

Various factors impinge on the ability of a solid insulator to withstand electric stress. Factors such as voids, impurities, and tracking have been discussed in previous sections. There is a common process that links all of these factors, that is the production of the material. It is the manufacturing process that generates the voids and impurities that are found in the finished product. To ensure that these do not affect the intrinsic electric strength of the material it would be necessary to 'purify' the manufacturing process, but production purification is costly. However, statistics can play an important part in the certification of materials to a certain 'purity' or quality of production. There are two theories that are applicable in this case:

Weibull statistics: this has been used for many years in the field of predicting breakdown in materials and is well known and understood
Six Sigma: this is a relatively new theory that seeks to improve the quality of any manufacturing output
Both of the above theories will now be discussed relating their application to the subject of interest.

5.1 Weibull Statistics

There exists both a two-parameter and a three-parameter Weibull distribution developed in the 1950s [28, 29, 30]. The two-parameter distribution is the most commonly used for characterising time to failure for solid insulators. Under constant DC or AC voltage conditions the cumulative probability of failure of a solid insulator, $P_F(t)$ is given by Equation 5-1.

$$P_F(t) = 1 - \exp\left\{-\left(\frac{t}{\tau_c}\right)^a\right\} t \geq 0$$

Equation 5-1

Where t = time (s)

τ_c = characteristic time to breakdown (s)

a = shape parameter (usually $0.5<a<3.0$)

The Weibull distribution is used to place breakdown information in the format of a statistical distribution so that probability of failure can be noted for any time, t. It is based upon empirical observations of breakdown and the shape parameter a is adjusted to fit the distribution of any given material. The characteristic time to breakdown is the time taken for breakdown to occur when the probability of failure is 0.6321 (i.e. $P_F(\tau_c)$).

The cumulative probability of failure is shown in Figure 5-1 for various shape parameter values. It can be seen that as a increases the range of times that failure can occur in decreases. The shape parameter, a is selected to fit the empirical data collected during electric strength tests.

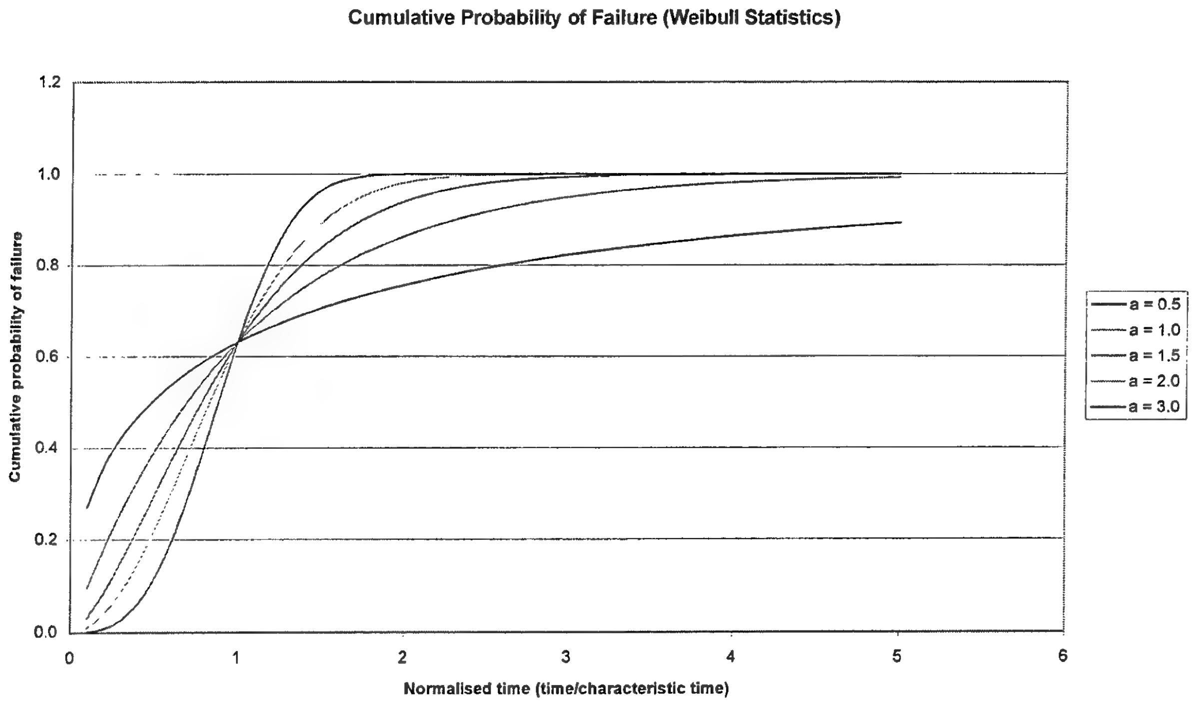

Figure 5-1: Cumulative probability of failure

It can be seen that as *a* increases prediction of failure becomes more accurate. As already stated, *a* is defined by the statistical spread of the empirical data and varies depending on the material type.

The two-parameter Weibull distribution is widely accepted as the most appropriate distribution for describing breakdown in solid insulators. It is used by the IEEE Electrical Insulation Society's Statistics Technical Committee [31]. At the present time the distribution has only been linked with data collected from breakdown under constant AC and DC conditions. It would be interesting to see how the distribution fits with breakdown data taken under transient stress conditions. This data has not been found during this study and requires generating using one of the methods discussed in the previous section before analysis can take place.

The three-parameter Weibull distribution includes an inception time before which breakdown cannot occur. The effect of this parameter, known as the location parameter, t_I is to re-locate the x-axis by a factor of t_I. The three-parameter Weibull distribution is given in Equation 5-2.

$$P_F(t) = 1 - \exp\left\{-\left[\frac{t - t_I}{\tau_c}\right]^a\right\} \; t \geq t_I$$

Equation 5-2

$$P_F(t) = 0 \; t < t_I$$

The only application of the three-parameter Weibull distribution in describing breakdown in solids seems to be where electrical treeing is induced after a specific time. In other cases, the location parameter is usually set to zero resulting in the more generally appropriate two-parameter distribution.

5.2 Six Sigma

Six Sigma [32] is a quality methodology developed by Motorola in the 1980s. Its aim is to significantly improve the production process to reduce variation in product performance. Six Sigma has been widely adopted in the US and it has been shown to be applicable to any size of business. Traditionally, manufacturing defects have been talked about in terms of percentages or parts per hundred. Six Sigma enhances the quality of a production process to a level that discusses failure rates in terms of parts per million. The methodology stems from traditional statistical approaches that used a sigma scale to define how much of a products or processes normal distribution was contained within a specification. As the sigma value increases the probability of a defect occurring in either the product or the process decreases. For a Six Sigma process the number of defects expected is of the order of 3.4 parts per million, an improvement over the traditional three sigma processes that resulted in defects of approximately 66 810 parts per million.

The Six Sigma process uses a stringent quality procedure that involves all levels of the workforce. Steps such as defining the boundaries, evaluating the process, analysing and improving the process and control are re-visited continually to ensure that the high quality output is maintained.

Earlier sections of this report have discussed the influence that manufacturing flaws have on breakdown in solid insulators. By improving the production process and reducing the number of voids and particulates in the insulator the electric strength will be increased. If all manufacturing flaws could be removed then the electric strength should be that of the materials intrinsic electric strength. It is possible that the adoption of such a process as Six Sigma would help to reduce the probability of the finished insulator product containing defects that contribute to an earlier than expected breakdown under electric stress.

5.3 Summary

This section has concentrated on two processes that are relevant to breakdown in solid insulators. Weibull statistics is widely used in this field when considering breakdown under either DC or AC conditions. Investigations are required before confirming the suitability of applying this method of failure prediction to breakdown in solids under fast transient conditions.

Six Sigma is a manufacturing process that seeks to improve the quality of an output by reducing the number of defects. It may be appropriate that a process such as Six Sigma be used as a means of reducing the manufacturing flaws that contribute heavily to the early onset of breakdown in solid insulators (with respect to their intrinsic electric strength). There are clearly issues involving production costs that would need to be considered by manufacturers before adopting any improvement process.

If an insulator is produced to a quality system that ensures that defects are met in terms of parts per million (such as Six Sigma) then the affect will be to increase the value of the shape parameter a in the Weibull distribution. This is an important point and highlights the link between the manufacturing process and the statistics involved in describing breakdown in terms of a distribution.

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6 Conclusions and Recommendations

This section contains conclusions of the review and some recommendations for further work.

6.1 Conclusions

This report has investigated the problem of breakdown in solids under transient conditions. A historical review of research in this field has been completed covering not only solid breakdown but also liquid and gas breakdown. Time spectral analysis has been completed on two UWB waveforms highlighting the frequencies at which the energy content of the pulses occurs. It has been shown that typical UWB pulses can not be thought of in terms of DC or low frequency AC signals as these types of pulses do not contain any frequency content occurring at less than 1MHz.

The mechanism of breakdown in solid, liquid and gas insulating materials have been reviewed and discussed. Particular detail has been paid to the mechanisms that occur in solids as this is of primary interest to this study. In particular voids, discharges, field distortion and thermal effects have been shown to be instrumental mechanisms in breakdown in solids.

Various measurement techniques have been discussed that are used to characterise a materials electric strength. A test cell set up has been proposed in order to measure the electric strength of insulators under fast transient conditions (for example, UWB pulses). Material characteristics and their affect on electric strength has been examined. Loss tangent (dielectric loss) measurements made on both polyethylene and Perspex have been investigated in relation to the materials' electric strength. It has been found that as the loss tangent increases the electric strength decreases. Further investigation is required to ensure that the measurement of loss tangent at various frequencies is incorporated into any analysis. In particular, extending the measurements to include THz frequencies (i.e. sub-picosecond regime) would allow inclusion of the range of frequencies that may invoke electron relaxation. It would be interesting to see the value of the loss tangent in the THz regime. If electron relaxation plays a part in breakdown then the loss tangent should be high at the relevant frequencies. It is worth noting that ionisation does not occur until approximately 3×10^{15} Hz (3 PHz) as the energy required to break an atomic bond is significantly higher than that achieved by frequencies of the order of THz. THz frequencies relate to energy of the order of 10^{-3} eV (meV) compared to a required energy of approximately 12.4 eV for ionisation to occur.

Zener theory has been investigated as it was developed as a method of explaining insulator electric strength with the use of quantum tunnelling. This theory has been applied to polymers that typically have band gaps of the order of 7eV. The electron tunnelling rate for a band gap of this order does not show any significant increase until approximately 125MV/cm, however, breakdown in polymers is known to occur at approximately 2.5MV/cm. It has been suggested that the electric strength suggested by Zener Theory be considered as a value for the intrinsic electric strength of an insulator. This implies that the impurities introduced into the material during the manufacturing process contribute significantly to a reduction in the electric strength of the insulator.

Repetitively pulsed systems have also been considered. Thermal effects relating to specific prf's will influence the electric strength of a material. It may become necessary to restrict the prf in order to reduce the probability of thermal breakdown occurring.

Statistical models have been reviewed. Weibull statistics has been used for many years to describe the spread of breakdown data collected under DC or low frequency conditions. It is necessary to collect breakdown data under fast transient conditions before the Weibull distribution can be seen to be applicable.

6.2 Recommendations

It is recommended that further work into the subject of this report is concentrated on collecting data on breakdown in solids under fast transient conditions (nano-second regime). However, before this can begin careful design of the test cell proposed in section 4.5 is required. Once designed the cell should be tested and validated for its suitability for this task. Data collected can then be analysed for its fit within a Weibull distribution and can be compared against theory and data already available for breakdown under DC or low frequency AC conditions.

In parallel, development of a model using Computational Electromagnetics (CEM) to show the onset and evolution of breakdown in solids under fast transient conditions is necessary. These models should be validated against the data collected.

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A Annex

A.1 Dielectric breakdown models

The following annex gives further information about specific models and equations that may be used to describe breakdown in solid insulators.

A.1.1 Intrinsic electron breakdown models

Frohlich single electron criterion (e- phonon scattering only):

$$E^2 = \frac{m^* h\nu}{e^2 \tau_c{}^2 (E_I)(2n_\nu + 1)}$$

Equation A-1

Where

E = breakdown electric field

E_I = ionisation electron energy for e-lattice collisions

τ_c (E_I) = e-phonon collision time at energy E_I

$n_\nu = \left(\frac{1}{e^{\left\{\frac{h\nu}{kT}\right\}} - 1} \right)$ phonon distribution function, Bose distribution for a lattice at temp T

e = electron charge

m^* = reduced mass (electron)

h = Planck's constant

k = Boltzmann constant

Frohlich amorphous solid collective electron model (includes consideration of e–e scattering):

$$E = Ce^{\left\{\frac{\Delta E}{2kT_0}\right\}}$$

Equation A-2

Where

E = Breakdown field

ΔE = Energy of band of shallow trap states

T0 = Temperature

k = Boltzmann constant

C is a slowly varying function of electron temperature-

$$C = \left[\frac{m^* n_\nu (T_0)}{e^1 \Delta E} \frac{C_2}{C_1} \right]^{1/2} \frac{h\nu}{e\tau_c}$$

Equation A-2.1

Where

$$C_1 = 2\left(\frac{2\pi\ m^* kT_e}{h^2}\right)^{3/2}$$

$$C_2 = NkT_e$$

N = density of trap band states

In this case the temperature has been set to the ambient lattice temp T_0.

A.1.2 Avalanche single electron breakdown model

$$E_A = \left(\frac{H}{\ln\left\{\frac{d}{E_A \mu(E)\tau(E)i}\right\}}\right) \qquad \textit{Equation A-3}$$

Where

E_A = Avalanche electron breakdown field

i = 30-40 (the typical no of avalanches required for breakdown)

d = insulation thickness

h = empirical constant [2]

$\mu(E)$ = mobility (for electrons at the ionisation energy E)

$\tau(E)$ = collision time (for electrons at the ionisation energy E)

A.1.3 Thermal breakdown models

Time dependent models:

Low field (field independent conductivity):

$$E = \left\{\frac{C_v D}{(a\sigma_0\tau)}\right\}^{1/2} e\frac{-aT_0}{2} \qquad \textit{Equation A-4}$$

Where

E = Breakdown field

τ = pulse width of the applied field

a = empirical constant

D = density

C_v = specific heat

(This is based on the conductivity: $\sigma = \sigma_0 e^{aT_0}$)

High field (field dependent conductivity):

Using the field dependent conductivity at field E and electron temperature **T** [3]:

$$\sigma = \sigma_0 e^{\{a(T-T_0)+bE\}} \qquad \textit{Equation A-4.1}$$

The breakdown field (E) is given by:

$$E = \frac{\left\{ \ln\left(\dfrac{C_v D}{a\sigma_0 \tau\, E^2} \right) - aT_0 \right\}}{b} \qquad \textit{Equation A-4.2}$$

Where a and b are constants.

When the Poole–Frenkel [4] mechanism comes into play (at high electric fields) we have:

$$E = \left\{ \frac{\phi - kT \ln\left(\sigma_0 E^2 \tau (\phi - \beta\, E^{1/2} \right) / C_v D k T_0^2}{\beta} \right\}^2 \qquad \textit{Equation A-4.3}$$

Where

E= Poole–Frenkel conductivity breakdown field E

β and ϕ are constants defined in the derivation of the Poole–Frenkel conductivity expression [1].

A.1.4 Electromechanical breakdown (Stark–Garton mechanism)

$$V = d_0 \left\{ \frac{Y}{\varepsilon_0 \varepsilon_r e^1} \right\}^{1/2} \qquad \textit{Equation A-5}$$

Where

V = Breakdown voltage

Y = Young's modulus of the dielectric

d_0 = initial dielectric thickness

A.2 Voids

Voids are generated during the manufacturing process of many dielectrics (particularly polymers). They can range in size from tens of nanometers (nm) to ~1mm.

The E field is greater in a void than in the surrounding solid dielectric by a factorε_r, the permittivity of the dielectric. At sufficiently high-applied E fields the void can breakdown before the surrounding dielectric. However, the statistical time lag tends to be long since the applied field will have swept the void free of electrons and the chances of a free electron appearing in a small volume (due to background radio activity etc) will be low. When a discharge does start electrons and ions will tend to accumulate at opposite ends of the void and thus oppose the applied E field. In this way the discharge will tend to extinguish itself (the charges accumulate because they can only move much more slowly through the insulating solid medium).

An equivalent circuit for a void has been given [1]. Calculations (using a complicated model) and experiment have shown that the discharging activity in a void is greatest when the applied E field is changing most rapidly [1]. However, the detailed behaviour of voids can be difficult to analyse because of the many interacting processes involved. An important demarcation is that between a Townsend discharge and a streamer discharge. The latter occurs at higher applied fields and is much more damaging to the dielectric, leading to rapid deterioration of the solid insulator material.

Threshold breakdown voltage (V) across a void is given by Equation A-5 [1]:

$$V = \frac{AIpd}{\ln\left\{\frac{Apd}{\ln\left(\frac{1}{\gamma\ (E/p)}\right)}\right\}}$$ *Equation A-6*

Where

γ (E / p) = Townsend secondary ionisation coefficient of the gas at E / p

p = gas pressure in void

E = electric field across the void

I = ionisation potential of gas

$$A = \frac{1}{pl}$$

l = electron mean free path length in the gas

A.3 Free volume

Free volume (typical size ~10 nm) is a feature of the amorphous polymer solid-state structure.

A correlation has been found [5] between the breakdown strength of many polymers and the cohesive energy density (CED) defined by:

$$CDE = \frac{H - RT}{V}$$ *Equation A-7*

Where

V = molar volume

R = gas constant

H = heat of vaporisation

A.4 Summary

The results above represent the end points of many of the principal theories and models of breakdown in solid dielectrics. Supporting experimental evidence is available for most of these theories [1].

The breakdown electric strength of a dielectric depends very much on how it is measured. The intrinsic electron breakdown models refer to geometry in which electron effects dominate; i.e. thin samples of material between plane electrodes. Thermal effects are not significant since any heat generated can escape rapidly. In measurements, such an arrangement will yield the highest measurable values of electric strength; in reality for thick samples of material under practical conditions the electric strength may be several orders of magnitude lower. Thermal models of breakdown are required for these cases. However, more variables then need to be included e.g. the means of heat removal from the dielectric which will of course depend on the geometry (so that cables and plane capacitors will behave differently). All models aim to find a breakdown field – defined broadly as the conditions under which charge carriers are just able to gain more energy from the electric field than they loose by collisions and other dissipative mechanisms. In the case

of avalanche breakdown (BD) the BD field is that at which more electrons are generated by collisions leading to a runaway increase in the number of charge carriers.

Electromechanical BD can come into play in the case of large area electrodes separated by thin films of dielectric. It may also become significant for example in the region of a protruding metal feature (introduced by accident or design) where the E field is increased and the dielectric thickness reduced. In such areas of high stress, runaway conditions may develop, thinning the dielectric leading to higher fields and this in turn producing greater mechanical stress etc.

Partial discharge is a complex process; it is important since it can lead to degradation of the dielectric and eventual failure. Complex models for the BD of voids and free volume have been developed and broadly validated by experiment [1]. These processes lead to 'tree' formation in solid dielectrics.

A common feature of the above models is that they tend to be general in nature. It is possible to apply them to specific materials but more details are then required (for example, on the trapping state structure of a given dielectric). There are some models available which only require bulk material properties for example the free volume and electromechanical mechanisms. It may also be possible to relate parameters like the loss tangent to physical quantities in some models.

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10a. Abstract. (An abstract should aim to give an informative and concise summary of the report in up to 300 words).

This report critically reviews currently available information on the subject of fast transient breakdown in solid dielectric insulators. Information is readily available on breakdown in solids under DC or low frequency conditions, as research into these areas has been driven by the power generating industries over many years. However, pulsed systems are generally constructed using safety factors or DC breakdown values for incorporated insulators. More recently fast transient (sub-nanosecond) breakdown in gases has been researched due to the use of gases in spark gaps.

The mechanisms involved in breakdown in solids under DC and low frequency AC conditions have been discussed and the relevance of these to breakdown under fast transient conditions has been explored. Also, theories that are pertinent to breakdown in solids under fast transient conditions have been reviewed. Measurement techniques for the collection of breakdown data have been examined and a test cell for the investigation of breakdown under fast transient conditions has been proposed. Statistical models that are used to describe breakdown in solids have also been discussed.

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